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16. Abstract A number of investigations have confirmed that, within the area of disability glare, a summation formula is applicable to several discrete glare sources. In the case of a larger glare surface, the sum passes to an integral, and it can be shown that this addition thoerem is also applicable to extensive glare sources. An earlier study by Hartmann and Moser has already shown that the summation formula is no longer valid at small glare angles. The present study shows that for both circular and radial glare sources, the equivalent veiling luminance at constant glare angle and constant illumination of the cornea increases more rapidly with increasing glare-source brightness as the glare angle diminishes. Deviations from additivity are noted for glare angles less than 2°. Whereas the additivity of equivalent veiling luminance follows clearly from the theory of light scattering, the explanation for the non-additivity of equivalent veiling luminance for very small glare angles is still uncertain at the present stage of knowledge. Retinal interactions as well as involuntary eye movements could be considered in such an explanation.

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EFFECT OF SIZE OF GLARE SOURCE ON DISABILITY GLARE AT SMALL GLARE ANGLES

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In various studies (e.g. Holladay 1926 [1], Crawford 1936 [2], Adrian 1961 [3], Hartmann 1961 [4]), a simple addition theorem was derived and confirmed for physiological (disability) glare. This theorem states that the total veiling luminance L_S of several glare sources present in the field of vision is equal to the sum of the veiling luminances L_{S_i} of the individual glare sources. Using the usual formulation for veiling luminance, this situation can be represented as follows: /20*

$$L_S = \sum_{i=1}^{m} L_{S_i} = k \sum_{i=1}^{m} \frac{E_{H_i}}{\Theta_i^n} = k \sum_{i=1}^{m} \frac{L_{B_i}\, \omega_{B_i} \cos \Theta_i}{\Theta_i^n} \qquad (1)$$

or in the integral formulation for continuous glare sources:

$$L_S = \tilde{k} \int\int \frac{L_B(\Theta, \varphi)}{\Theta^n} \sin \Theta \cos \Theta \, d\Theta \, d\varphi \qquad (1a)$$

where L_S is in cd/m^2; E_H is the intensity of illumination of cornea in lux; θ is the glare angle in degrees; L_B is the luminance of the glare source in cd/m^2; ω_B is the spatial angle in sr subtended by the glare source; and k is a constant with a numerical value of about 10, although substantially larger values can also occur. (There is no point in using decimals such as 9.4 or 9.6 in the calculation, because this would just feign an accuracy and a generality which are not really available.) $n \approx 2$; differences of up to 30% and more are found, depending on the measuring

* Numbers in the margin indicate pagination in the foreign text.

technique, the experimental setup, the age of the test subject, etc. (The comment regarding the value of k applies here as well. Two is at best a usable mean value.) The index i refers to the i-th glare source. Moon and Spencer, 1943 [5] and Altmann, 1965 [6] assumed the lower limit of the glare angle θ at which formulas (1) and (1a) are still valid to be $\theta = 1°$.

The addition theorem is easy to understand, if one starts from the physical causes of glare, namely, the light scattering in the media of the eye (e.g. Vos, 1962 [7]). However, this addition theorem appears not to hold at small glare angles, as will now be explained.

With an experimental setup depicted schematically in Fig. 1, the additivity of veiling luminance was checked for small angles. In one case, the glare source was situated in a ring around the point on which the test symbol was projected, so that the glare angle remained strictly constant in a fixed measuring situation, even when the size of the glare source was varied (Fig. 1a). Various fixed glare angles were provided (θ = 0.5°, 1°, 2°, 3.5°); θ is the glare angle between the line connecting the center of the eye with the test symbol and the line

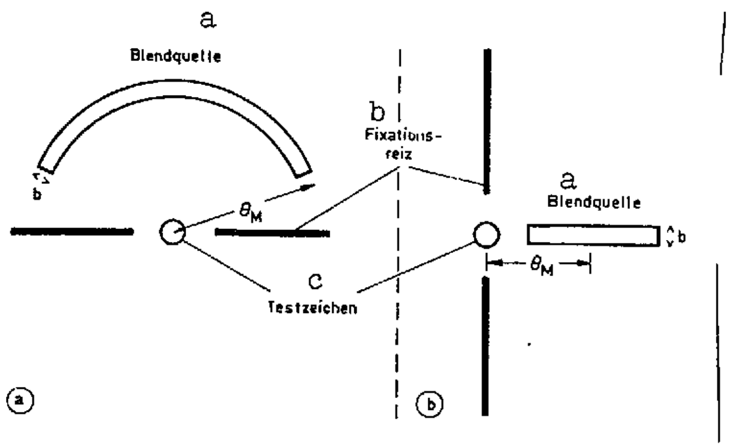

Fig. 1. Experimental setup for testing the addition theorem of veiling luminance. Fig. 1a depicts a ring-shaped glare source, with which the luminance (or glare source size) can be varied while holding cornea illumination and glare angle constant. Fig. 1b shows a radial glare source, in which the angle θ_M is held constant as glare source luminance is varied.

Key: a. Glare source; b. Fixation stimulus; c. Test symbol connecting the center of the eye with the glare source. In addition, the length and luminance of the glare source could be varied by a factor of 100, independently of each other. In this way, the length and thus the size of the glare source could be varied, and by suitably matching the luminance, the illumination of the cornea could be held constant. In the other case, a radial glare source was employed. The setup is shown in Fig. 1b. The radial glare source was placed horizontally next to the test symbol, and its length and luminance were likewise variable, so that constant cornea illumination could be achieved for any glare source size. In both arrangements, the width b of the glare source was always 3 mm, and the test subject was placed 3.5 m away. As a result, the width of the glare source was at most 3', and could therefore be neglected in comparison with the glare angle (the minimum was 30').

Together with a background of 400' and a background lumi- /21
nance of 0.5 cd/m^2, two thin black strips were projected, which served as fixation stimuli for the test symbol appearing in the middle.

The test symbol, a disc 4' in diameter with positive contrast, was presented in alternating rhythm in the center of the homogeneous background. Starting from subthreshold values, the test subject adjusted the luminance of the test symbol so that it could just be recognized in a given glare situation (threshold measurement). Because of the alternating rhythm, which the subject had to recognize correctly, the probability of guessing was lowered, while the threshold was increased. The total illumination was produced with incandescent lamps, and parabolic mirrors were used for the glare source. The subject looked with both eyes. With the setup described, it was in particular possible to determine whether, with constant angle θ and constant cornea illumination E_H, but variable L_B (or ω_B, since $E_H = L_B \cdot {}_B \cdot \cos\theta \approx L_B \cdot \omega_B$, due to the fact that $\cos\theta \approx 1$ for small angles), the veiling luminance L_S

did in fact remain constant in accordance with the addition theorem. In the case of the ring-shaped glare source, this is immediately evident, while a more careful scrutiny of the radial glare source setup also shows this to be true.

First, the angle-dependence of disability glare was tested with a "point" glare source (size 3 × 3 mm^2, equivalent to $7.6 \cdot 10^{-7}$ sr) in order to determine the extent to which the values for the constants k and n given at the beginning in the Holladay formulation were reproducible. By a point source, we mean that the diameter of the glare source (expressed in min) is small compared to the angle θ. For a cornea illumination E_H = 0.2 lux, similar values were obtained, as reported by Hartmann and Moser (1968) [8] in their work. In the representation:

$$L_S = k \frac{E_H}{\Theta^n} \qquad \begin{array}{l} L_s \text{ in cd/m}^2 \\ E_H \text{ in lux} \\ \Theta \text{ in degrees} \end{array}$$

the following values were obtained for n and k:

$20' \leq \Theta \leq 90'$	$k_2 = 32$	$n_2 = 3.3$
$90' < \Theta$	$k_1 = 22$	$n_1 = 2.4$

For angles larger than 90', the values for k_1 and n_1 agree in satisfactory fashion with those given in the literature, taking into consideration the facts that inexperienced test subjects were employed, and that starting from subthreshold values, the test symbol had to be adjusted until it was just recognizable. At any rate, the size of the constants plays practically no role in the proof of the nonadditivity of veiling luminance.

The strange-looking value of 90' at which the values of n and k change is merely a convenient value for computational purposes. In reality, there is probably a transition region in which k and n vary continuously.

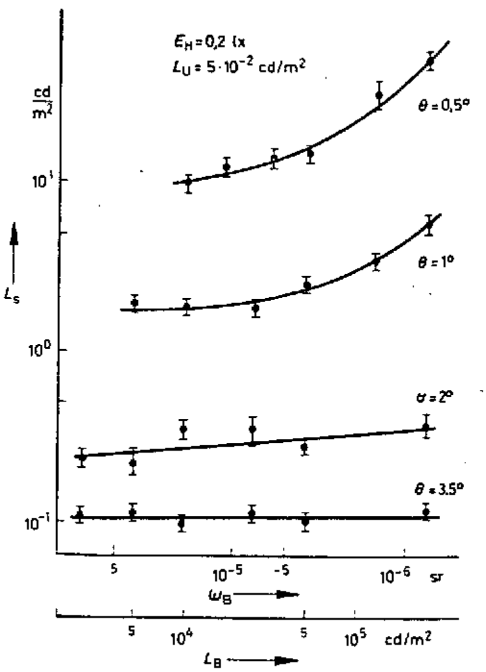

Fig. 2. Veiling luminance L_S as function of glare source luminance L_B or glare source size ω_B with a ring-shaped glare shource with constant illumination E_H of the cornea. Parameter: glare angle θ.

The reported values of k and n have an error of $\leq \pm 10\%$.

Fig. 2 shows the results of measurements for the circular glare source and various fixed glare angles, corresponding to various radii of the circular arcs. The veiling luminance L_S is plotted as a function of glare source luminance L_B (or the glare source size ω_B, since $L_B \cdot \omega_B = E_H = 0.2$ lux). The curve parameter is the glare angle θ.

Fig. 3 shows the corresponding results for radial glare sources, and the glare angle θ_M functions as a parameter in this case as well. With the ring-shaped glare source, the glare angle was automatically held constant, even when the glare source was expanded along the circle. However, in order to maintain the glare angle with a radial glare source, the latter must be enlarged symmetrically on the inside and the outside, because only then will the center of the glare source remain fixed. Although such a measure would not have been necessary with the ring-shaped glare source, the glare source was enlarged symmetrically in that case as well.

The measured points were obtained in the usual fashion by taking mean values. In order to minimize any possible adaptation influences at the beginning of the measurements and fatigue manifestations at the end, the measurements for each glare angle

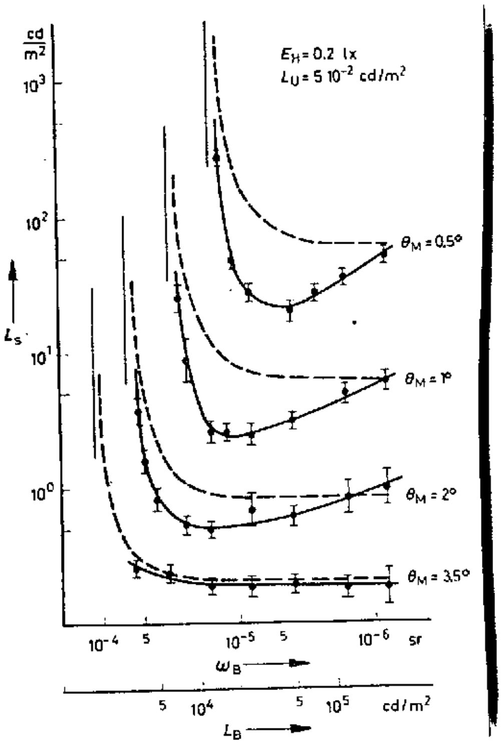

Fig. 3. Veiling luminance L_S as a function of glare source size ω_B or glare source luminance L_B for a radial glare source. The parameter is the angle θ_M to the middle of the glare source. The measured values are connected with a solid line. The values computed from the addition theorem are indicated by the broken lines, where $\omega_B = 7.6 \cdot 10^{-7}$ sr was taken as a reference value.

were taken once as the glare source luminance was being increased in the sequence of measurements, and once as it was being decreased. The tests were conducted with a total of three test subjects.

As for results: If the addition theorem were valid without restriction, the curves in Fig. 2 would have to be straight, horizontal lines. This is in fact the case for the glare $\theta = 3.5°$, but there are obviously deviations for smaller glare angles -- namely, as luminance /22 increases, i.e. glare source size decreases, the veiling luminance clearly rises; the smaller the glare angle, the greater the rise.

The results in Fig. 3 are somewhat more complicated to interpret. For an extensive (in the radial direction) glare source, the glare angle is not uniquely defined. The center of the glare source is not a suitable reference point for calculating the veiling luminance L_S, since the formula is not linear in the glare angle, but involves the inverse square. A meaningful "center of glare" θ_S can now be defined as follows:

For the glare angle of an extended glare source (of luminance L_1 and spatial angle ω_1) with cornea illumination E_H, we select that angle θ_S which a point glare source (of luminance L_2 and spatial angle ω_2) of the same cornea illumination E_H makes with the test symbol when the point glare source produces the same veiling luminance L_S as the extended glare source.

With the aid of Fig. 4, this situation can be expressed mathematically for a radial glare source whose width b is small in comparison with the glare angle θ. Since E_H = constant, and $\cos\theta \approx 1$ (which holds for the present measurements) we have:

$$E_H = L_1 \cdot \omega_1 = L_2 \cdot \omega_2$$

or, since the width b is to be the same for both cases:

$$L_1(\Theta_{12} - \Theta_{11}) = L_2(\Theta_{22} - \Theta_{21}) \cdot$$

The veiling luminance L_S can then be expressed as:

$$L_S = k^* \cdot L_1 \cdot \int_{\Theta_{11}}^{\Theta_{12}} \frac{1}{\Theta^n}\, \Theta = k^* \cdot L_2 \cdot \frac{\Theta_{22} - \Theta_{21}}{\Theta_s^n} \cdot$$

The factor k* should contain all quantities not directly relevant, such as conversion factors and the width b of the glare sources.

With all the simplifications mentioned, we finally obtain:

$$\Theta_s^n = \frac{(\Theta_{12} - \Theta_{11})\,(n-1)}{\Theta_{11}^{1-n} - \Theta_{12}^{1-n}} \cdot$$

For other extended glare sources, one must resort to the integral formulation of the addition theorem, which requires a greater effort in calculation.

If the veiling luminance is calculated using the formula:

$$L_S = k \frac{E_H}{\Theta_s^n}$$

where the values given at the beginning for n and k are employed, valid results are obtained in the case of the glare angle $\theta_M = 3.5°$ (broken line in Fig. 3), while deviations appear for $\theta_M \leq 2°$.

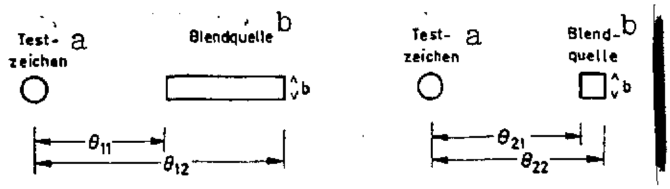

Fig. 4. Clarification of the definition of the "center of glare" for a glare source extended in the radial direction (details in text).

Key: a. Test symbol; b. Glare source

Thus, for the radial glare source as well, veiling luminance is nonadditive at small glare angles.

Figs. 2 and 3 also show that extended glare sources in the region of small angles do not have as great a physiological effect as small, point glare sources of the same corena illumination. This state of affairs is very familiar in psychological (discomfort) glare.

However, this situation has frequently been reported in the literature for (physiological) disability glare as well. For instance, Legrand (1937)[9] and Eichoff (1962) [10] refer to it in their works. Nevertheless, the measurements were in general taken with rather large glare angles and glare-source spatial angles. Hence, the effects found have always been very small.

Myasoyedova (1968) [11] likewise dealt with the nonadditivity of veiling luminance. However, a formula she gives for calculating the veiling luminance of a linear glare source furnishes no reasonable results in the present case, since it yields a negative veiling luminance.

The interpretation of the nonadditivity of veiling luminance found here is still somewhat speculative for the time being.

Let us first consider the influence of the pupil. According to investigations of Adrian (1964) [12], with an illumination of the cornea of 0.14 lux, the pupil width does not change as the spatial angle of the glare source varies between 10^{-3} to almost 10^{-6} sr. However, this statement holds for a fixed glare angle of 5°, while the present investigation is concerned with smaller angles. There is no reason to assume that, as the glare angle becomes small, pupil width will suddenly start to undergo large changes as the size ω of the glare source varies. Furthermore, estimates have shown that even if the pupil had a large influence, this still could not account for the change described for veiling luminance in relation to glare-source size ω for small glare angles. However, measurements with an artificial pupil would be able to clarify this point.

At the start, we pointed out that the addition theorem for veiling luminance was plausible if the cause of the glare effect was assumed to be light scattering in the media of the eye. However, it is now very likely that additional processes play a role when the glare angle is small. For example, neuronal interactions in the retina (particularly for small glare angles) could have an influence (receptive fields). Involuntary eye movements might also be important.

In any case, no satisfactory explanation for the results /23
presented can be derived from the present material. The direction of this work is rather to determine the limits of validity of the addition theorem and to indicate trends.

Further investigations on this topic are in progress at the Institute for Medical Optics.

It is true that these results, including the preliminary indications in the work of Hartmann and Moser [8], have practically no significance for interior lighting, since there the glare angles are as a rule substantially larger than 3°. This investigation also has no particular importance for street lighting, since, first, the light intensity of a reasonable street lamp is no longer very high at 87°, and, second, the illumination of the cornea from a distance of 170 m, measured by the adaptation level, also no longer attains large values. However, the situation with automobile headlights is quite different. When encountering oncoming traffic on narrow roads, glare angles of less than 3° down to 0.5° are even normal. For this reason, we should not attempt to raise the brightness of headlights, and thus made the headlights smaller. Instead, the indisputable advantages of modern halogen lamps should be exploited, together with regulation of beam range, to provide a better distribution of brightness on the street.

Thus, for example, the right headlight, because of its greater glare angle, normally produces a smaller glare effect than the left headlight, so that its range could be increased, and the light intensity of the left headlight could be reduced somewhat in the significant glare zone. It can easily be shown that better illumination of the lane can be obtained in this way without increasing glare.

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